Regional maps of occupational heat exposure: past, present, and potential future

Olivia M. Hyatt[1], Bruno Lemke[2] and Tord Kjellstrom[1,3,4]*

[1]Health and Environment International Trust, Nelson, New Zealand; [2]Nelson Marlborough Institute of Technology, Nelson, New Zealand; [3]National Centre for Epidemiology and Population Health, Australian National University, Canberra, Australia; [4]Centre for Global Health Research, Umeå University, Umeå, Sweden

Background: An important feature of climate change is increasing human heat exposure in workplaces without cooling systems in tropical and subtropical countries. Detailed gridded heat exposure maps will provide essential information for public health authorities.

Objectives: To develop and test methods for calculating occupational heat exposures and present results in easily interpreted maps.

Design: Published formulas for a common occupational heat exposure index, the WBGT (Wet Bulb Globe Temperature), were used in combination with global gridded climate data to calculate heat exposure in $0.5°$ grid squares. Monthly averages of daily maximum temperatures, as indicators of typical temperatures during the hottest part of the day, and corresponding water vapour pressures produced estimates of monthly WBGT indoors (without cooling systems) or outdoors in the shade.

Results: The maps show the WBGT within selected hot regions of the world during the three hottest months in 1975 and 2000: Australia, South Asia, Southern Africa, Central America, and southern US. Between 1975 and 2000 a WBGT increase of $0.5–1°C$ was common and the maps show clear decreases in some places. The time trends fit with the development of global climate change. The high WBGT values (particularly in South Asia) already cause excessive occupational heat exposures during the three hottest months. If continued climate change increases WBGT by $3°C$, our maps identify areas where occupational heat stress in non-cooled workplaces will be extreme.

Conclusions: The mapping method provides a rapid visual impression of occupational heat exposures in large regions of the world. The local changes in WBGT between 1975 and 2000 fit with the global climate change trends. Future increases of WBGT may create extreme heat exposure situations in large areas of the world.

Keywords: *climate change*; *heat stress*; *work*; *occupational health*; *modelling*; *GIS*

Heat exposure in the working environment is an often overlooked but important part of occupational health (1, 2). It can cause several potential negative health outcomes such as death from heat stroke, damage to major organs, and physiological functions (3). Quantitative exposure-response relationships are available in the literature for some of these effects [e.g. Wyndham (4) and Axelsson (5)]. Impacts on health and productivity at an individual level have been studied and published by physiologists and ergonomists for decades [see reviews of Parsons (1) and Bridger (3)].

In high income countries in temperate parts of the world, the focus in heat and health research has been on clinical health effects during 'heat waves' (6), as it is assumed that most of the year the temperatures are not hot enough to cause heat-related health effects. However, in tropical and hot parts of subtropical countries heat stress is occurring during large parts of each year (in some places almost every day), and cultural practices (e.g. siesta, reduced work intensity, large hats) have provided effective ways to adapt to the hot environment (1).

Muscles work at about 20% efficiency so for every kW of work done, the muscles produce 5 kW of heat. If that heat is not dissipated, it will remain in the body and core body temperature will rise. While some physiological acclimatisation can occur to improve heat loss mechanisms

(increased peripheral vasodilatation and increased sweating) (3), this process has its limits. For example, once ambient temperature is above approximately 34°C, the basic laws of physics tell us that no more heat can be lost by convection or radiation (indeed there is heat gain when ambient temperature is above 37°C). Once the relative humidity is above about 85%, heat loss by evaporation of perspiration also ceases and, instead, sweat drips off the body as a result taking no heat energy with it (3). There are no other significant heat loss mechanisms other than moving to a cooler environment or to reduce the heat generated inside the body. Which means less physical work is possible and this will affect the economy of heat exposed communities. As temperatures rise due to climate change, less work in non-cooled environments will be possible in hot countries.

The Wet Bulb Globe Temperature (WBGT) is a common measure of occupational heat stress (1). While there are a number of measures of heat exposure and discomfort, which integrate assessments of people's perception of heat into the values (1), the WBGT has the advantage of being based solely on actual environmental variables. It combines temperature, humidity, wind speed, and heat radiation in a more detailed manner than the simpler 'heat index' and 'humidex,' which can be used as approximate heat screening measures. Modern computer methods make it reasonably easy to calculate WBGT even with the rather sophisticated formulas required. The US military carried out extensive research in the 1950s and 1960s into the physiological ability of soldiers to withstand high temperatures, which lead to the adoption of WBGT as a measure of health and work capacity relevant heat stress capable of causing clinical health effects including fatalities (1).

If WBGT is above safe limits and a worker does not reduce physical labour input, the risk of serious health effects (e.g. heat stroke, and in extreme cases, death) increases (4), resulting in productivity decline if the worker gets too ill to work. If however, WBGT is high and the worker reduces her/his physical labour activity by taking more and longer rest periods in order to reduce clinical health risk as recommended by the international standard (7), the hourly productivity will decrease. Consequently, a competing situation occurs between health protection of workers and the maintenance of productivity in the work environment (8).

A recent paper from China (9) demonstrated the effect of heat exposure and work intensity during physical work in experimental conditions in terms of 'heat tolerance time' (defined as the time until core body temperature reaches 39°C or the subject gets so exhausted that she/he stops the physical activity). Increasing the heat exposure quantified as the WBGT from 34 to 38°C cuts the heat tolerance time by more than half at each level of work intensity. If a person works beyond the heat tolerance time, the risk of clinical heat strain and heat stroke is likely to be increased to a similar extent.

There is growing concern that anthropogenic climate change will increase the risk of serious heat exposure to workers, particularly in already hot countries with poor resources to prevent any increasing risks (10). No estimates of the impacts of workplace heat on populations in relation to climate change have been published except some tentative analysis (11, 12). Recently, globally gridded maps of heat stress on human populations in 1975 and modelled future heat stress in 2045 using the German heat index HeRATE (13) have been published. This index has not been used for interpretation of likely impacts of workplace heat exposure, while WBGT was developed and tested for such impact analysis (1).

The purpose of this short paper is to illustrate with maps the past and potential future spatial patterns and changes in occupational heat exposure (as indoor WBGT during the hottest hours of a day) in four geographic regions. The potential implications for health and work productivity of the measured and estimated heat stress will also be discussed briefly, as an element of climate change that requires preventive policies and actions not only to protect the health of working people but also their productivity and the impacts on the local economy.

Present investigation, methods, and materials

Variables for maps
The WBGT levels indoors (or outdoors in the shade) were calculated for the hottest hours of the day during the three hottest months in 1975 and 2000 for four global regions: Australia, South Asia (India, Pakistan, Bangladesh, Nepal), Southern Africa (Gabon, Congo, Uganda, Kenya, and all countries to the south), and Central America and the southern US (all of Central America, Mexico, and US south of a line from San Francisco to New York). A further series of maps for the same months and regions were produced for a scenario where 3°C is added to the WBGT in the year 2000. The 3°C addition for the hottest part of the day is similar to the increase of WBGT at noon if the workplace is outdoors in the sun. This difference between shady and sunny workplaces would obviously depend on the clarity of the air, any variability in cloud cover, and the angle of the sun in relation to the ground.

For example, when the sun is close to zenith during May in Delhi, the additional WBGT in the sun is 5–6°C (14), but this is likely to be an extreme case. Thus, we consider 3°C to be a realistic estimate of the difference. This increase of WBGT is also in line with what may occur due to climate change, because it is close to the middle of the range of estimated average global temperature increase this century (15) and our calculation method would produce such an increase of WBGT if air temperature

increases 3.3–4°C (depending on changes in humidity levels; Lemke, unpublished observations).

WBGT levels in each grid square were calculated based on global gridded monthly data from the Climatic Research Unit, University of East Anglia (version CRU TS 2.0) via a freely available program 'TYTEN' (16). The data comes in a 0.5° resolution grid (50 × 50 km at the equator), over the globe (excluding Antarctica), with 67,420 grid boxes. Out of the nine variables available, files of temperature (.tmp), maximum temperature (.tmx), and water vapour pressure (.vap) from 1961 to 2002 were extracted and used in our calculations.

The Wet Bulb Globe Temperature (WBGT) calculations

A number of researchers have calculated the outdoor WBGT from standard meteorological data (17). Four factors influence outdoor WBGT: air temperature, humidity, air movement (wind speed), and heat radiation (outdoors from the sun). Solar heat radiation is a difficult component to determine because of variable cloud cover. Wind speed is often very variable during the course of a day. Because of these issues we have chosen to calculate WBGT indoors, which does not require solar data. We assumed that wind movement over the skin was 1 m/s, which is similar to the speed of arm and leg movements during physical work and walking. The outdoor values for WBGT in the shade are similar to the indoor values with only a small additional component from diffuse solar radiation. During very hot days, it is likely that people will avoid working in the direct strong sunlight if they can. Therefore, the maximum indoor WBGT values may represent exposure levels for most working people, except those that have access to air conditioning in the workplace or are forced to work in full sun.

The WBGT for each grid square was calculated from the standard WBGT formulas (1):

Indoor WBGT: $WBGTid = 0.7 Tnwb + 0.3 Tg$
Outdoor WBGT: $WBGTod = 0.7 Tnwb + 0.2 Tg$
$+ 0.1 Ta$,

where Tnwb is the natural wet bulb temperature, Tg is the black globe temperature, and Ta is the ambient temperature.

Indoors and outdoors in the shade $Tg = Ta$ so the indoor formula becomes:

$WBGT = 0.7 Tnwb + 0.3 Ta$.

Further, Bernard and Pourmoghani (18) have developed a formula for Tnwb:

$Tnwb = Ta - (0.96 + 0.069 \log_{10} V)(Ta - Tpwb)$,

where V is the wind speed in m/s and Tpwb is the psychrometric wet bulb temperature (the wet bulb temperature in the shade with a 3 m/s wind blowing over it).

For a wind speed = 1 m/s (which we used as a standard value) the formula becomes:

$Tnwb = 0.96 Tpwb + 0.04 Ta$; and
indoor $WBGT = 0.67 Tpwb + 0.33 Ta$.

To calculate Tpwb accurately, iterative processes need to be used, but for this analysis we opted for a faster and approximative method of calculating the Tpwb:

$$Tpwb = 0.066 \times Ta + 4098 \times VP \times Td/(Td + 237.3)^2)/$$
$$(0.066) + 4098 \times VP/(Td + 237.3)^2$$
$$(19),$$

where Ta is the ambient temperature (C), VP is the vapour pressure in kilo-Pascals, and Td is the dew point temperature (C) and is equal to:

$$Td = 243.5 \ln(VP/0.6112)/(17.67 - \ln(VP/0.6112). (20)$$

This method gives good results (less than 2% error) at the higher temperatures (greater than 25°C) with humidity greater than 50%. At lower humidity and lower temperatures, the error increases to be about 5% overestimation of WBGT for 30% humidity at 25°C. To get the average daily WBGT for the hottest hours (usually the afternoon), the monthly average of the maximum daily temperatures (Tmax) was used for the ambient temperature (Ta) in the above formulas.

The WBGT calculations for each grid square were carried out by using a spreadsheet (Microsoft Excel 2007). Checks were made for consistency on latitude/longitude vector points, and the months and years were checked to ensure that they were consecutive. Most data was processed while in vector form as this gave maximum calculation flexibility.

We calculated WBGT indoor values for two time points. Values for the year 1975 were an average from 1965 to 1985, whereas the values for the year 2000 were generated by a fitted regression line of annual data from 1980 to 2002 for each month.

Map production

The resulting WBGTs for each month were exported in ASCII raster files, which were imported into a GIS program (Quantum). The WBGT scale on the maps is subdivided into three 'risk levels' (WBGT <25: Low risk; 26–33: moderate to high risk; and 34+: extreme risk). These risks were based on the occupational health standard (7) and various national standards that recommend hourly rest periods during heavy labour when WBGT reaches 26°C and no work when WBGT reaches 34°C. A reduction of work capacity to 25% during 1 h is equivalent to a WBGT of 31°C for heavy work and WBGT of 32.5°C for light work (7). For WBGT levels less than 26°C, the effects (even among people doing high intensity work) is not likely to cause heat strain.

The top row of the maps shows indoor WBGT during the hottest part of the day, during the hottest 3 months in 1975. The middle row presents estimated WBGT in 2000 for the same months, and the bottom row shows the 2000 data plus 3°C for WBGT in each grid square. The bottom row can represent WBGT levels outside in the sun in 2000, or the indoor levels later this century increased by climate change.

In addition to the maps, examples of WBGT levels from a few individual weather stations in major cities of each region were compared with the values in the corresponding grid squares. The weather station levels were calculated from daily NOAA climate data for 2000 (these can be bought from NOAA for a limited fee). The weather station WBGTs are the monthly averages of reported daily Tmax for each month.

Present investigation, results

Figs. 1–4 illustrate WBGTs for the three hottest months for each region in 1975, 2000, and the scenario of +3° WBGT from 2000.

In Australia, moderate to high risk of heat strain are widespread in the northern half of the country in 1975 and in 2000. In some areas, the calculated WBGT and risk for heat strain has actually decreased from 1975 to 2000 (Fig. 1). Such changes towards lower WBGT are associated with a reduction of humidity. The problems of increasing droughts in parts of Australia are well known (21, 22). For agriculture and essential water supply it is a major problem, but the maps show that a reduction of heat stress may also occur.

There are strips adjacent to the southern and eastern coasts of Australia as well as Tasmania that have low heat strain risk in 1975 and 2000. The majority of Australia would be in the moderate to high risk WBGT under the +3° scenario and some of the north-western areas would experience extreme heat strain risk (Fig. 1).

In South Asia, the heat strain risk is generally moderate to high (Fig. 2) and the apparent trends from 1975 to 2000 are towards higher WBGTs. When 3°C is added, extreme heat strain risk is seen over a large proportion of India and Pakistan. May is the hottest of these 3 months.
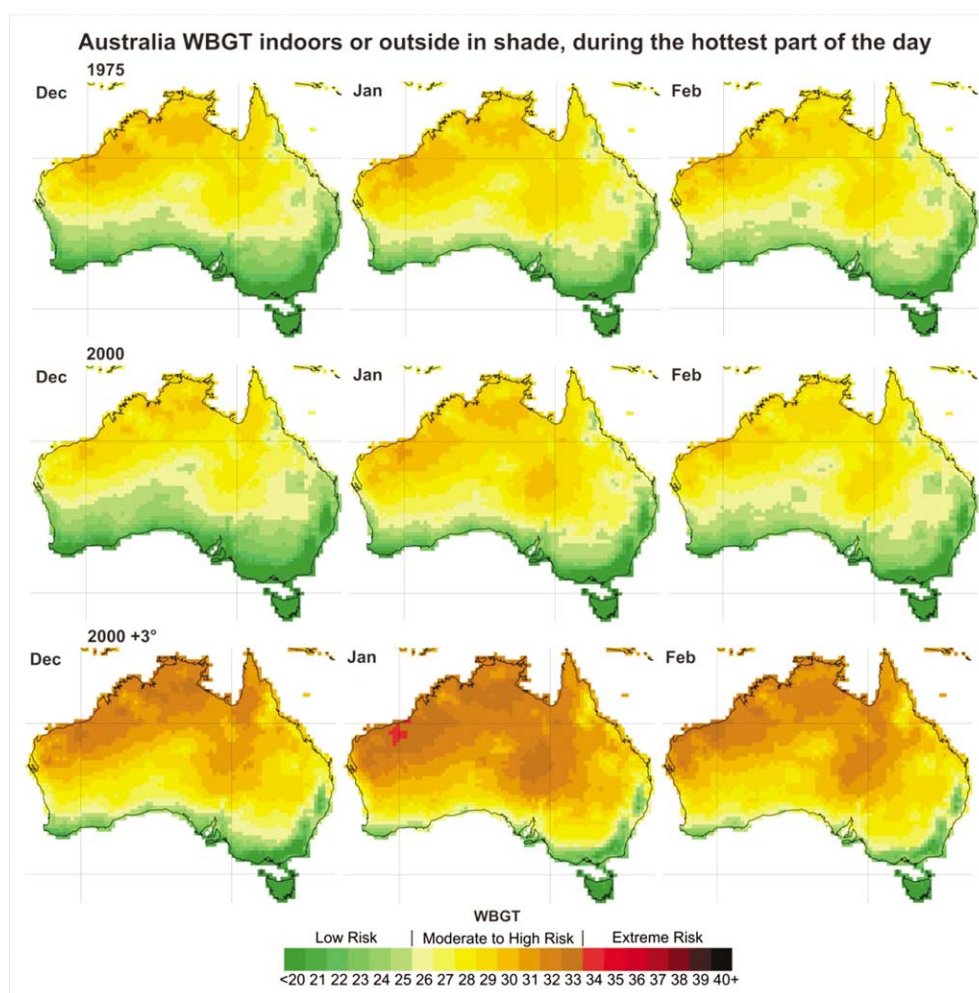
Fig. 1. WBGT (indoors and outside in the shade) for Australia in 1975, 2000, and a scenario where WBGT is increased by 3° from the year 2000.
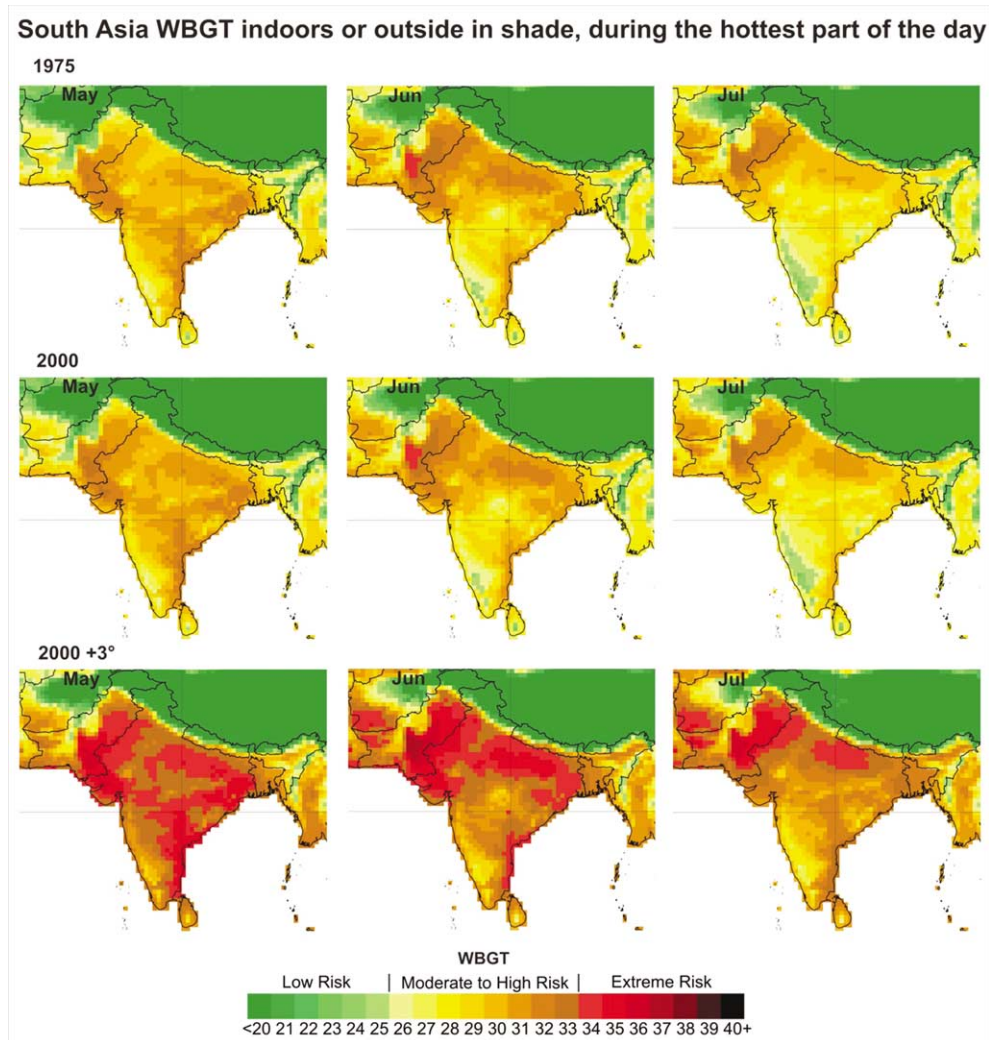
Fig. 2. WBGT (indoors and outside in the shade) for South Asia in 1975, 2000, and a scenario where WBGT is increased by 3° from the year 2000.

In Southern Africa between 1975 and 2000, there is an increase of WBGT within the low risk range, illustrated as lighter green in 2000 than 1975 (Fig. 3). There appears to be little change in areas of moderate to high risk between 1975 and 2000. Under the +3°C scenario, most of Southern Africa would be in the moderate to high risk zone and an area at the border between Kenya and Somalia would be in the extreme risk category.

In the fourth region analysed (Fig. 4), July and August have the largest of moderate to high heat strain risk and between 1975 and 2000 there is a clear shift towards higher WBGTs. The changes in Central America are less obvious than those occurring in the southern parts of the US (Fig. 4). In the +3°C scenario, substantial areas of the southern US and Central America will transition into high risk and some areas will develop extreme risk.

The actual changes in WBGT calculated for each grid square in the four regions are shown for the same months in Fig. 5. Generally, changes between 0 and 1°C have

occurred in the regions with some visible variations. In some places WBGT was reduced during this period often due to a drier climate rather than reduced temperatures. WBGT is dependent on both temperature and humidity in our calculations.

Australia has the largest areas with constant or reduced WBGT in December and February, but most of these grid square areas are in deserts or other central areas with very small local populations. In Table 1, we summarise the changes of WBGT for each region in a more quantitative manner. The reduced WBGT in December and February in Australia is quite clear, but in January the WBGT shift is towards higher values as it is for each of the three hot months in each of the other three regions (Table 1).

Discussion

There is little difference in WBGT heat exposure levels between 1975 and 2000 in Australia and Southern Africa
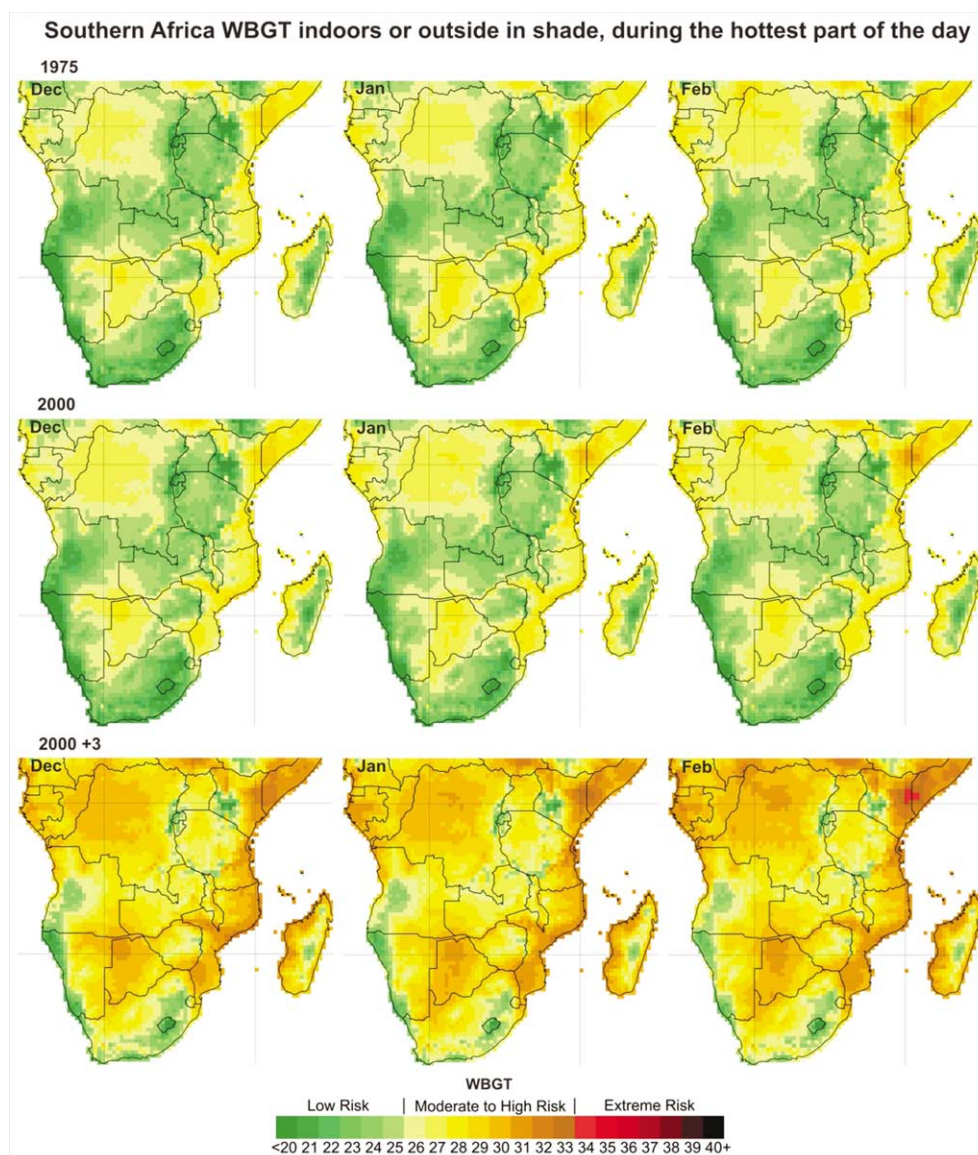
Fig. 3. WBGT (indoors and outside in the shade) for Southern Africa in 1975, 2000, and a scenario where WBGT is increased by 3° from the year 2000.

(Figs. 1 and 3). In contrast there has been an apparent increase in WBGT levels in parts of South Asia, Central America, and the southern US (Figs. 2 and 4). The maps are an efficient way of getting a rapid impression of heat stress levels and heat strain risks in geographic areas around the world. This paper is a first stage in a project to assess heat stress impacts on working people with modelled levels of future climate change. Our results show that changes in WBGT may be small until now, but large areas of these four regions are already experiencing moderate to high heat strain risk during the hottest hours of the hottest months. A useful aspect of this type of map presentation is the ability to see interregional variability changes through time and with different scenarios.

The maps for 1975 and 2000 show the calculated indoor WBGT. These heat exposure levels are also indicative of the outdoor WBGT in shaded workplaces including the exposures for working people who have taken action to avoid working in the strong sunlight. The maps with the additional 3°C show the WBGTs and the heat strain risks for people working in the sun during the hottest hours of the day (the afternoon). Outdoor workers in large parts of the four regions are at high or even extreme risk of heat strain. As pointed out by Kjellstrom et al. (8), the workers in these situations need to take lots of rest to protect their health and this will reduce hourly productivity during daylight hours. This fits with the examples of work patterns during heat stress that was highlighted by Kjellstrom (10): Construction workers and
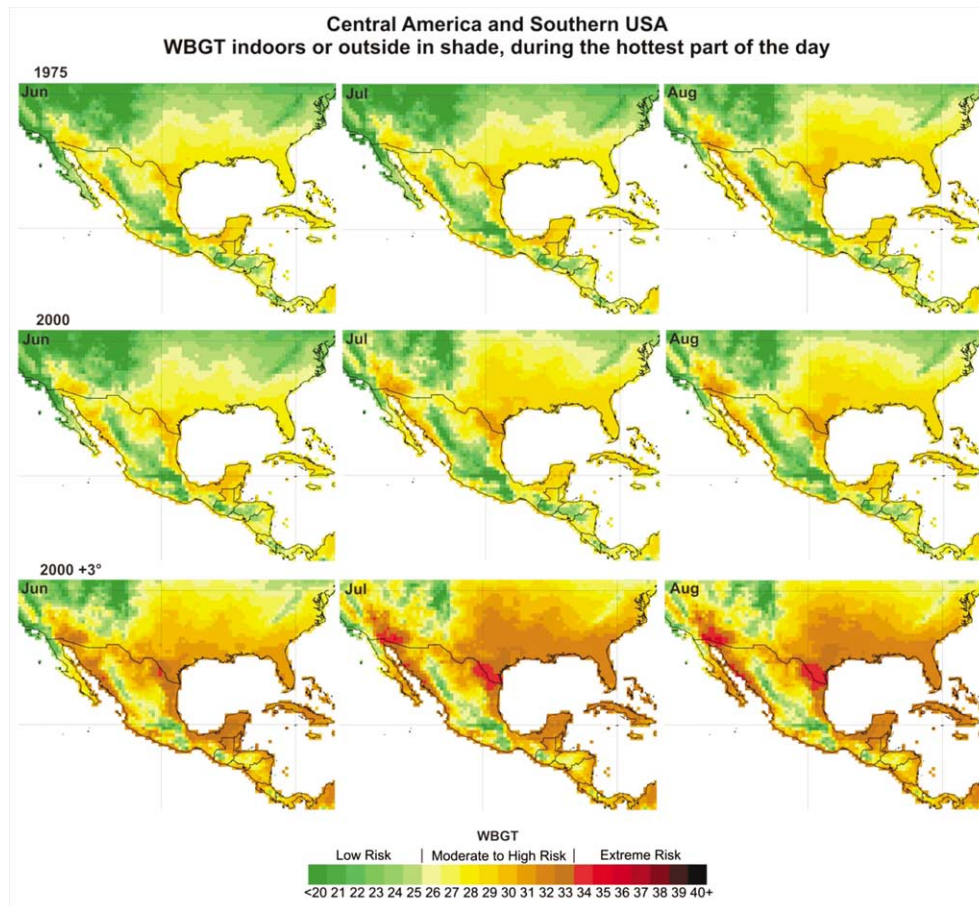
Fig. 4. WBGT (indoors and outside in the shade) for Central America and the southern US in 1975, 2000, and a scenario where WBGT is increased by 3° from the year 2000.

some agricultural workers just took the afternoons off, and in some factories additional workers are employed to make sure the necessary work can be carried out in spite of the heat.

The impact on work capacity and productivity depends on the application of cooling methods at work and the distribution of the workforce. If outdoor hard physical work is common in a population, the impacts of the calculated heat stress is greater than in populations where most people work indoors in air conditioned spaces. The first tentative estimate of the impact on work capacity of current and future heat stress (12) showed that heat-related productivity losses would occur in almost all regions of the world.

It should be pointed out that occupational health is seriously jeopardised when workers are not able to take sufficient rest during heat stress or not able to prevent dehydration due to excessive sweating. One example from the US, is the still occurring heatstroke-related mortality among immigrant farm workers (23), which is associated with work-output-linked-pay that discourages the necessary rest breaks.

While the addition of 3°C to the 2000 WBGT levels is a somewhat crude scenario of climate change impact on heat exposure, it is not out of line with the potential changes in these areas of the world as mentioned earlier. The estimated WBGT increase indoors or in the shade depends on temperature and humidity and one methods study (Lemke, unpublished observations) indicates that WBGT would increase at between 0.77 and 0.95 times the temperature increase, depending on whether absolute humidity stays the same or relative humidity stays the same. Thus, a WBGT increase of 3°C can occur when temperature increases 3.1–3.7°C, which is within the range of climate change impacts suggested by IPCC (15).

Jendritzky and Tinz (13) investigated heat stress in respect to people's comfort levels and acclimatisation through time, which includes adaptive measures such as clothing or personal protective equipment (PPE). The WBGT models used in this study does not include adjustments related to the perception of heat stress and only uses climate variables. However, the estimated increase of the number of days per year with high perceived heat stress (13) occurs in the same areas where
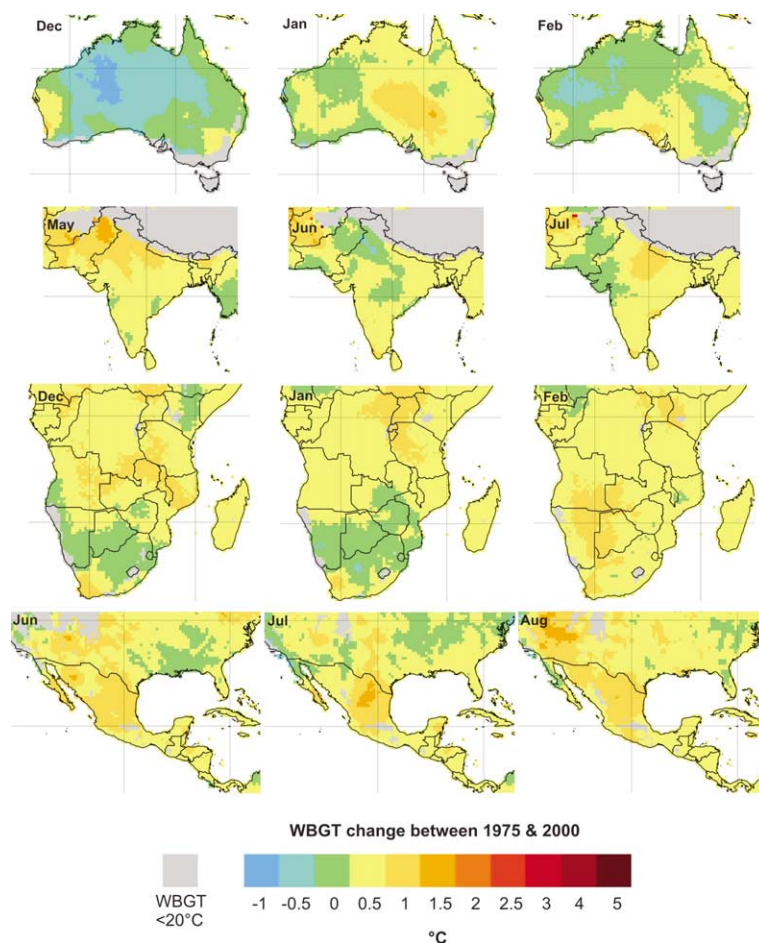
Fig. 5. Difference between 1975 and 2000 in WBGT of grid squares above 20°C WBGT (grids of <20°C are coloured grey).

our maps show high WBGTs. More detailed comparisons are needed to establish whether a real correlation exists between the different assessment methods, which are not based on the same criteria.

A recent analysis of heat stress risks in the general population calculated the occurrence of peak heat stress in the form of Tpwb in gridded patterns around the world and displayed the frequency distributions of different maximum heat exposure levels (24) based on four recordings per day. The highest levels were most likely at midday. Based on mapping of the current climate (mean 1999–2008), no place had Tpwb higher than 31°C and a climate model for current level showed similar results, while a model run that increases global average temperature by several degrees C was needed to bring maximum Tpwb up above 35°C, the threshold for serious heat strain at rest assumed by the authors (24). As our heat strain risk assumptions include the internal heat production from work and physical activity, our maps show high heat strain risk areas already in the year 2000. With an addition of 3°C to WBGT, great problems to carry out work will occur in many places as our maps show.

Another recent analysis for Perth, West Australia, was carried out with quite different methods, but again using climate modelling until 2070 to identify the impacts on human activities (25). The model estimated an increase of annual mean temperature in Perth at 6°C, and this increase was assumed to occur each day of the year. Thus, the annual distribution of daily heat exposures in the period 1990–2001 was scaled up with the same shape for the year 2070. Very elaborate heat balance models for sweating and heat transfer between a body and the environment were used to calculate how many days a 2.5°C increase of core body temperature in less than 2 hours would occur at different physical activity levels (25). The result showed that the number of days that physical activities, including work, could not be carried out (to avoid serious heat strain) was substantially increased due to the modelled climate change. The report said that in 2070 'manual labour will be dangerous to perform on 15–26 days per year compared to 1 day per year at present' (25). Our maps of the southern part of West Australia indicate the ongoing and potential future heat stress, which this calculation for Perth highlights.

Table 1. Summary of changes of WBGT from 1975 to 2000, number of grid squares with specific ranges of change of grid squares in 1975 and 2000 with WBGTs above 20°C

Area	Month	Total grid squares[a]	WBGT change 1975 to 2000, °C							
			−2 to −1.5	−1.5 to −1	−1 to −0.5	−0.5 to +0.5	0.5 to 1	1 to 1.5	1.5 to 2	>+2
Australia	December	2,589	0	154	1192	1,233	10	0	0	0
	January	2,665	0	0	6	2,298	355	6	0	0
	February	2,665	0	0	321	2,304	40	0	0	0
South Asia	May	1,563	0	0	0	1,097	433	33	0	0
	June	1,580	0	0	15	1,493	68	4	0	0
	July	1,584	0	0	0	1,420	164	0	0	0
Southern Africa	December	4,173	0	0	0	3,507	666	0	0	0
	January	4,218	0	0	14	3,793	411	0	0	0
	February	4,235	0	0	0	3,585	650	0	0	0
Central America and southern US	June	2,647	0	0	0	1,867	768	12	0	0
	July	2,771	0	0	10	2,308	415	38	0	0
	August	2,758	0	0	0	1,897	774	87	0	0

[a]The total number of grid squares for each month varies because some grid squares have WBGT <20°C during certain months.

Regional maps of occupational heat exposure

Conclusions

The visualisation through maps of changing heat stress is a useful tool in conveying the change in spatial and temporal patterns. All four regions have experienced some changes in WBGTs between 1975 and 2000. In South Asia and the southern US, the calculated WBGT levels are generally increasing, while in parts of Australia the levels are decreasing due to reduced humidity. With a 3°C increase of WBGT from 2000, most areas within all four regions are in the moderate to high risk of occupational heat strain. As a consequence, there potentially will be significant occupational health risks associated with workplace heat in these regions as a result of rising heat exposure due to climate change.

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References

1. Parsons K. Human thermal environment. The effects of hot, moderate and cold temperatures on human health, comfort and performance. 2nd ed. NY: CRC Press; 2003.
2. Kjellstrom T, Hogstedt C. Global situation concerning work-related injuries and diseases. In: Elgstrand K, Pettersson I, eds. OSH for Development. Stockholm: Royal Institute of Technology; 2009 pp. 741–61.
3. Bridger RS. Introduction to ergonomics. London: Taylor and Francis; 2003.
4. Wyndham CH. Adaptation to heat and cold. Env Res 1969; 2: 442–69.
5. Axelsson O. Influence of heat exposure on productivity. Work Environ Health 1974; 11: 94–9.
6. Hajat S, Armstrong BG, Gouveia N, Wilkinson P. Mortality displacement of heat-related deaths: a comparison of Delhi, Sao Paulo and London. Epidemiology 2005; 16: 613–20.
7. ISO. Hot environments – Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). ISO Standard 7243. Geneva: International Standards Organization; 1989.
8. Kjellstrom T, Holmer I, Lemke B. Workplace heat stress, health and productivity – an increasing challenge for low and middle income countries during climate change. Global Health Action 2009; 2. DOI: 10,3402/gha.v2i0.2047. Available from: http://www.globalhealthaction.net/index.php/gha/article/viewArticle/2047/2541 [cited 10 November 2010].
9. Zhao J, Zhu N, Lu S. Productivity model in hot and humid environment based on heat tolerance analysis. Building Environ 2009; 44: 2202–7.
10. Kjellstrom T. Climate change, direct heat exposure, health and well-being in low and middle income countries. Global Health Action 2009; 2: 1–4. DOI: 10.3402/gha.v2i0.1958. Available from: http://www.globalhealthaction.net/index.php/gha/article/view/1958/2183 [cited 10 November 2010].
11. Kjellstrom T. Climate change, heat exposure and labour productivity. Epidemiology 2000; 11: S144.
12. Kjellstrom T, Kovats S, Lloyd SJ, Holt T, Tol RSJ. The direct impact of climate change on regional labour productivity. Int Archives of Environmental & Occupational Health 2009; 64: 217–27.
13. Jendritzky G, Tinz B. The thermal environment of the human being on the global scale. Global Health Action 2009. DOI: 10.3402/gha.v2i0.2005. Available from: http://www.global-healthaction.net/index.php/gha/article/viewArticle/2005/2528 [cited 10 November 2010].
14. Kjellstrom T. Climate change exposures, chronic diseases and mental health in urban populations – a threat to health security, particularly for the poor and disadvantaged. Technical report to the WHO Kobe Centre. Kobe, Japan: World Health Organization; 2009.
15. IPCC. Fourth Assessment Report. Geneva, Inter-governmental Panel on Climate Change. Cambridge: Cambridge University Press; 2007. Available from: http://www.ipcc.ch [cited 10 November 2010].
16. Solymosi N, Kern A, Maróti-Agóts A, Horváth L, Erdélyi K. Software, data and modelling news: TETYN: an easy to use tool for extracting climatic parameters from Tyndall data sets. Environ Model Software 2008; 23: 948–9.
17. Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg 2008; 5: 645–55.
18. Bernard TE, Pourmoghani M. Prediction of workplace wet bulb global temperature. Appl Occup Environ Hyg 1999; 14: 126–34.
19. Jensen ME, Burman RD, Allen RG, editors. Evapotranspiration and irrigation water requirements. ASCE mnual and report on Engineering Practices No. 70. NY: American Society of Civil Engineers; 1990, p. 332.
20. Brice T, Hall T. Wet-bulb calculator; 2009. Available from: http://www.srh.noaa.gov/epz/?n=wxcalc [cited 10 November 2010].
21. CSIRO. Climate change, the latest science. Report to Parliament; 2009. Available from: http://www.csiro.au/files/files/pp3c.pdf [cited 10 November 2010].
22. Whitaker R. The complete book of Australian weather. Sydney: Allen & Unwin; 2010.
23. MMWR. Heat-related deaths among crop workers – United States, 1992–2006. JAMA 2008; 300: 1017–8.
24. Sherwood SC, Huber M. An adaptability limit to climate change due to heat stress. PNAS 2010; 207. DOI: 10.1073/pnas.091 3352107.
25. Maloney SK, Forbes CF. What effect will a few degrees of climate change have on human heat balance? Implications for human activity. Int J Biometeorology 2010; 54. DOI 10.1007/s00 484-010-0320-6.

*Tord Kjellstrom
Health and Environment International Trust
168 Stafford Drive, Mapua
Nelson 7005, New Zealand
Email: kjellstromt@yahoo.com